

“Extraterrestrial Studies Using Nuclear Interactions”

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Summary

Cosmogenic nuclides were used to study the recent histories of the aubrite Norton County and the pallasite Brenham using calculated production rates. Calculations were done of the rates for making cosmogenic noble-gas isotopes in the Jovian satellite Europa by the interactions of galactic cosmic rays and especially trapped Jovian protons. Cross sections for the production of cosmogenic nuclides were reported and plans made to measure additional cross sections. A new code, MCNPX, was used to numerically simulate the interactions of cosmic rays with matter and the subsequent production of cosmogenic nuclides. A review was written about studies of extraterrestrial matter using cosmogenic radionuclides. Several other projects were done. Results are reviewed here with references to my recent publications for details.

Cosmogenic Nuclides in Various Meteorites.

Cosmogenic nuclides in several meteorites were modeled using calculated production rates. Cosmogenic nuclides are made by a range of nuclear reactions, ranging from neutron-capture reactions to high-energy spallation reactions. Calculations are done using Monte Carlo numerical simulations codes such as the LAHET Code System (LCS) and the Monte Carlo N Particle eXtended (MCNPX) code. Comparisons with measured activities of radionuclides in a variety of meteorites are good tests of these codes. The calculated production rates are used to get cosmic-ray exposure ages and irradiation geometries from the cosmogenic nuclide measurements.

Norton County.

Norton County is one of the stony meteorites with the longest exposure age, about 107 Myr. It is an aubrite, which has a very low concentration of iron. This low iron concentration means that the fluxes of thermal neutron in it are very high. Both spallogenic and neutron-capture nuclides were measured by Herzog, Bogard, and co-workers in 11 samples of Norton County with known irradiation depths. These results were modeled with calculated production rates. Some variations might be due to composition variations among the samples. Some of the measured ^{36}Ar was made by the decay of ^{36}Cl . A preliminary report of the results is in Fink et al. (2002) and in a paper in preparation.

Brenham.

Brenham is a stony-iron pallasite that was very large in space. Many cosmogenic radionuclides and noble-gas isotopes have been measured in numerous metal and stony samples from pieces of Brenham. Production rates of spallogenic nuclides in pallasites are slightly higher because of their high iron content. Many of the measurements are for both metal and stony phases that were located very close to each other. Preliminary work on using calculated production rates to model these data (Kollar et al., 2003) generally show good agreement between calculations and measurements and indicated that Brenham was ~4-6 meter in radius in space. Some of the cross sections used in the calculations need to be improved.

Cosmogenic Nuclides in Europa.

Cosmogenic nuclides in surface samples of the large satellite of Jupiter Europa could be measured to determine how long those samples were on the European surface. Europa is very geologically active, and surfaces there are believed to be fairly young and continuously modified. A series of calculations were done of cosmogenic-nuclide production in Europa (Swindle et al., 2003). The surface material was assumed to be salts deposited on the surface from those dissolved in an ocean below the ice surface of Europa. The fluxes of energetic particles irradiating the European surface were the galactic cosmic rays (GCR) and protons trapped in the Jovian magnetosphere. Recent measurements of these trapped protons at Europa showed very high fluxes (which give high doses and are

why the Galileo spacecraft spends most of its time much further from Jupiter). The spectral shape of these protons is like those in a soft solar particle event (relative few high-energy protons), but the flux is ~1000 higher than the average solar-proton flux at the Moon. Thus, like the Moon, cosmogenic nuclides in the surface of Europa made by both high-energy GCR and lower-energy particles. However, the trapped protons at Europa dominate over GCR production to depths of many centimeters. Work is now being done to see if the trapped protons produce enough secondary neutrons to be important and to study the effects of erosion on expected concentrations. A paper on these calculations is being prepared for publication.

Calculations of Cosmogenic-Nuclide Production Rates.

Work continues to be done on improving the calculated production rates for cosmogenic nuclides. My emphasis recently has been on getting better cross sections for the relevant nuclear reactions that make cosmogenic nuclides and on using a better code to numerically simulate the particle fluxes made in irradiated objects by cosmic-ray particles.

Cross Sections.

A paper was written and published (Kim et al., 2002) on cross sections for the production of ^{10}Be on targets of carbon irradiated by protons with energies between 40 and 500 MeV. These cross sections are among the last of the proton ones measured as part of a large effort during the last decade by Dr. Janet Sisterson and co-workers. These proton cross sections are being used to model nuclides made by solar protons and serve as initial estimates for neutron-induced cross sections.

I often worked with Dr. Sisterson on her work on measuring cross sections of cosmogenic nuclides using high-energy neutrons. She does her neutron irradiations at the iThemba Lab in South Africa and the Los Alamos Neutron Science Center. I work with her on applying her measured cross sections and on planning the targets and neutron energies for future irradiations. Several new irradiations will be done this year. These neutron-induced cross sections will be very important in good modeling of the production of nuclides by GCR particles because most nuclides are made by secondary neutrons.

Particle Fluxes Calculated by MCNPX.

The computer code MCNPX (Monte Carlo N Particle eXtended) is a new code that numerically simulates the production and transport of particles. It includes, in one code, well-coupled and improved versions of the LAHET (Los Alamos High Energy Transport) and MCNP codes that were run separately by the LAHET Code System (LCS). LCS has been used for cosmogenic-nuclide calculations for a decade but has some limitations, such as having to run LAHET and MCNP separately and having poor physics for the interactions of particles with energies above 3.5 GeV.

The MCNPX code was released for use about a year ago. My new post-doctoral research associate, Dr. Kyeong Kim, has been learning how to run this very complicated code. We only recently were able to get the sets of cross sections needed to run MCNPX. Results on neutron fluxes calculated with MCNPX were reported in Kim et al. (2003).

One set of results was a comparison of the calculated neutron and protons particle fluxes in a meteorite with a series of mono-energetic protons with those for the full spectrum of GCR protons. We are developing the capability to use our calculated particle fluxes with cross sections to get production rates of cosmogenic nuclides. We then will test our calculated production rates with cosmogenic radionuclides previously measured in lunar cores, such as the Apollo 15 deep drill core, and in well-characterized meteorites, such as Knyahinya.

Other Projects.

Solar-Proton Fluxes.

Solar-proton fluxes observed at Earth during the last few years have been quite high, as I noted in my 2002 paper at the 33rd Lunar and Planetary Science Conference. Since I wrote that abstract, I have updated my compilations of modern solar-proton fluxes using satellite measurements made near the Earth. Many fairly-strong solar particle events occurred during 2002 (March 16, March 22, April 17, April 20, May 22, July 7, July 16, July 22, August 14, August 17, August 22, August 24, September 6, and November 9) that have added significantly to the total flux for the current solar cycle. The proton fluxes in these events have been added to those in my database. Interestingly, there have been only a few very weak solar particles events from then until the end of March 2003. This database of modern solar particle events are used for comparisons with the fluxes determined from solar-proton-produced nuclides in lunar samples.

Review Articles.

I prepared a talk and wrote a paper for the 9th International Conference on Accelerator Mass Spectrometry (Nagoya, Japan, 9-13 September 2002) on recent studies of meteorites using cosmogenic radionuclides. This review complements one that I wrote the previous year on cosmic-ray interactions in the Moon and that was prepared to be in the book *New Views of the Moon* now being written. Several of these radionuclides are made by neutron-capture reactions (^{36}Cl , ^{41}Ca , and ^{59}Ni) and nicely complement the nuclides made by spallation reactions. Much work has been done with cosmogenic radionuclides on determined terrestrial ages, the length of time that a meteorite has been on the Earth's surface. For martian and lunar meteorites, these terrestrial ages are summed with their exposure ages in space to determine when they were ejected from their parent body. Cosmogenic nuclides can be used to determine the pre-atmospheric size and locations of samples in a meteorite. The 0.3 Myr radionuclide ^{36}Cl is now often used with stable ^{36}Ar to determine cosmic-ray exposure ages, including iron meteorites in which exposure ages determined from cosmogenic potassium have been determined.

At the request of Prof. Gregory Herzog, I reviewed and made many comments, corrections, and additions to a long review article ("Cosmic Ray Exposure Ages") that he was writing for the first volume in the 10-volume *Treatise on Geochemistry*. He discussed the many ways that cosmic-ray exposure ages are determined and reviewed results for stony and stony-iron meteorites, including micrometeorites.

Miscellaneous

Two presentations were made based on work done under this grant. One was the talk at the 9th International Conference on Accelerator Mass Spectrometry (Nagoya, Japan, 9-13 September 2002) that was the basis for the paper submitted to the Conference's proceedings (Reedy et al., 2003). I also gave a talk on "Cosmogenic Nuclides and the Recent Histories of Meteorites" to the Dark Matter Research Center at the Seoul National University in Seoul, Korea, on 17 September 2002.

I also reviewed two proposals on work related to cosmogenic nuclides.

Publications during April 2002 - March 2003 that were supported by NASA's Cosmochemistry Program (CCP):

1. D. Fink, P. Ma, G. F. Herzog, A. Albrecht, D. H. Garrison, D. D. Bogard, R. C. Reedy, and J. Masarik (2002) " ^{10}Be , ^{26}Al , ^{36}Cl , and non-spallation ^{36}Ar in the Norton County Aubrite," *Meteorit. Planet. Sci.*, **37**, Suppl., A46.
2. K. J. Kim, J. M. Sisterson, P. A. J. Englert, M. W. Caffee, R. C. Reedy, J. Vincent, and C. Castaneda (2002) "Experimental cross-sections for the production of ^{10}Be from natural carbon targets with 40.6 to 500 MeV protons," *Nucl. Instrum. Methods B*, **196**, 239-245.
3. K. J. Kim, D. M. Drake, and R. C. Reedy (2003) "Numerical Simulations of Cosmogenic Neutron Production and Transport in Planetary Surfaces," in: *Lunar and Planetary Science XXXIV* (Lunar and Planetary Institute, Houston, TX), CD-ROM, Abstract #1532.
4. D. Kollar, J. Masarik, K. Nishiizumi, and R. C. Reedy (2003) "Monte Carlo Simulation of Cosmogenic Nuclide Production in the Brenham Pallasite," in: *Lunar and Planetary Science XXXIV* (Lunar and Planetary Institute, Houston, TX), CD-ROM, Abstract #1670.
5. T. D. Swindle, R. C. Reedy, and J. Masarik (2003) "Production Rates of Noble Gases in the Near-Surface Layers of Europa by Energetic Charged Particles and the Potential for Determining Exposure Ages," in: *Lunar and Planetary Science XXXIV* (Lunar and Planetary Institute, Houston, TX), CD-ROM, Abstract #1466.
6. R. C. Reedy (2003), "Recent Advances in Studies of Meteorites Using Cosmogenic Nuclides," in: *Proceedings of the 9th International Conference on Accelerator Mass Spectrometry* (Nagoya, Japan, 9-13 Sept. 2002), *Nucl. Instrum. Methods B*, in review.